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FORUM
Toward Policies and Decision-Making for Dam Removal

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ABSTRACT / Dam removal has emerged as a critical issue in environmental management. Agencies responsible for dams face a drastic increase in the number of potential dam removals in the near future. Given limited resources, these agencies need to develop ways to decide which dams should be removed and in what order. The underlying science of dam removal is relatively undeveloped and most agencies faced with dam removal lack a coherent purpose for removing dams. These shortcomings can be overcome by the implementation of two policies by agencies faced with dam removal: (1) the development and adoption of a prioritization scheme for what constitutes an important dam removal, and (2) the establishment of minimum levels of analysis prior to decision-making about a dam removal. Federal and state agencies and the scientific community must encourage an initial experimental phase of dam removal during which only a few dams are removed, and these are studied intensively. This will allow for the development of the fundamental scientific understanding needed to support effective decision-making in the future and minimize the risk of disasters arising from poorly thought out dam removal decisions.

Dams have made a significant contribution to human development both in the United States and worldwide, and the benefits derived from dams are considerable (World Commission on Dams 2000). However, dams are also one of the most significant anthropogenic hydrologic disturbances in the United States (Graf 1999) and worldwide (Dynesius and Nilsson 1994, Vorosmarty and others 1997). The existence and operation of dams has already had greater hydrologic and ecologic impacts on American rivers than any changes that might reasonably be expected from global climate change in the near future (Graf 1999). Disturbance of American rivers by dams reflects a combination of the disproportionately profound effect of a small number of large dams with the cumulative impact of millions of small dams (Graf 1999).

During the first half of the twentieth century, construction of dams in the United States was supported by a strong mandate from both the general public and the federal government (e.g., the Flood Control Act of 1927) because of the value of dams for power generation (hydroelectric dams of the 1900s, simple 'millpond' dams of the 1800s), flood control, and water supply [see review of types and sizes of dams in the United States by the Heinz Center (2002)]. These dams provided valuable services at the local, regional, and national level and represent significant structural investments. Benefits associated with dam construction, however, are counterbalanced by prices to taxpayers and funding agencies and the effect of dams on the natural environment. The environmental influences of dams include short- and long-term effects on hydrology, stream morphology, and stream biota (Petts 1984, Ligon and others 1995, Power and others 1996, Shields and others 2000).

The functional lifespan of most dams is approximately 60–120 years because of gradual deterioration in structural integrity and reservoir infilling by sediment (Dendy and Champion 1978, American Society of Civil Engineers 1997). By the year 2020 more than 85% of the dams in the United States will be near the end of their operational lives (FEMA 1999). Repair and upgrading are routinely chosen as the best options to deal with aging and substandard dams. However, dam licenses are currently expiring in a significantly different regulatory and economic atmosphere than the one in which they were originally granted. Values and attitudes toward the natural environment have changed consid-

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erably since most original licenses were granted, requiring that agencies faced with relicensing must not only consider safety, but also values not considered during original licensing decisions (Bryant 1999). Additionally, there is often stark contrast between the need for dams at the time of their construction and the need for them many decades later. The services originally provided by small dams [generally less than 100 acre-ft impoundments (Heinz Center 2002)] are often no longer required, and the local community may instead value dams as historic structures or because of the unique, albeit artificial, habitat that they provide (Doyle and others 2000). Ownership of a small dam may have changed hands over the many years since its construction, and indeed an owner may no longer be known (i.e., abandoned dams). Ownership may then be assumed by a state dam safety agency, which then also assumes responsibility for maintenance (e.g., American Rivers and others 1999). For large dams, particularly in the western United States, the need for these structures typically has not diminished, as large metropolitan areas have often developed based on the water and/or power supplied from a complex array of dams. While both large and small dams had strong mandates for their construction, support for repair and maintenance today is often least for small dams.

Emergence of Dam Removal

Within these contexts dam removal has emerged as a major environmental management issue. This emergence could represent a fundamental shift in accepted policies of river management, for both management agencies and the general public. If such a fundamental shift in accepted attitudes towards rivers has occurred, then dam removal will become an increasingly common and sustained facet of environmental management. Alternatively, consideration of the removal option could be occurring within a temporary "policy window" (sensu Haeuber and Michener 1998), wherein technical or environmental problems, politics, and policy alternatives merge at a point in time: "when the discussion of solutions and problems coincides with a favorable political environment" (Haeuber and Michener 1998). A policy window does not mean that decisions to remove a dam are being made and carried out, but rather that for a certain period dam removal is at least discussed as a potential management decision. This policy window can close as the political environment changes, or if new scientific or technical issues emerge.

From the limited history of dam removal, several trends are emerging. First, the number of dams removed has increased rapidly over the past three decades, but almost all removals have been of small dams (Doyle and others 2000). A continued increase in the number of dam removals will be driven by the aging of dams, the increased attention to dam removal by the scientific and public communities, and the economic realities of dam removal and dam repair (discussed below). For small dams, there has been a fundamental and sustained shift in accepted attitudes towards one in which dam removal is seen as a viable option.

Second, discussion of the removal of large dams is occurring within unique policy windows, strongly controlled by the political environment (Grant 2001). For example, during the 1990s the US Army Corps of Engineers began scientific investigations to examine potential removal of dams on the Snake River (e.g., Wik 1995), signifying the beginning of a policy window during which dam removal was viewed as a viable alternative. In 2001, the Corps recommended against further consideration of dam removal (Verhovek 2001), signifying the end of the policy window because of technical difficulties for dam removal and/or because of a change in political climate.

Finally, dam removal is often promoted under the assumption that dam removal will be inherently beneficial simply because dam presence and operation are known to be detrimental to aquatic ecosytems. For example, Bednarek's (2001) examination of the ecological impacts of dam removal was based primarily on a review of the ecological impacts of dams, extrapolated to generate predictions of how dam removal would reverse these effects. The reality is that there is a profound lack of studies documenting the actual impacts of dam removal, although several are beginning to emerge (Kanehl and others 1997, Stanley and others 2002). While dam removal will likely benefit many components of local ecosystems, removing a dam may also wreak havoc. In the Midwestern United States, reservoirs provide a valuable, albeit unintentional, service as sinks for nutrients (Stanley and Doyle 2002) within the already nutrient-laden Mississippi Basin. In addition, sediment released following a dam removal will inevitably be harmful to many downstream flora and fauna, which may include groups of endangered species, like unionid mussels. Whether such detrimental impacts will be temporary phenomena, or whether they will be significant perturbations to already highly disturbed ecosystems has yet to be documented or even discussed. One must then consider that dam removal might "fail" in a sense, i.e., be contrary or inefficient with regard to particular goals, such as environmental restoration.

As dam removal, especially for small dams, begins to take a more prominent place in environmental management, developing criteria for decision-making becomes a critical issue. This is particularly true in light of the lack of dam removal policies in most state and federal agencies. Here, we investigate current modes of decision-making for dam removal and place these within a general conceptual framework for environmental decision-making. We discuss the current status of dam removal with respect to the available science and perceived purposes of dam removal. Based on this framework, we suggest two policies for various groups faced with decisions involving dam removal and show how these policies will aid in refining our scientific understanding and help decision-makers clarify their key objectives in dam removal. Our suggestions are in some respects similar to those published in this journal by Pejchar and Warner (2001). Although their views and suggestions were based around proposed dam removals for restoration of anadromous fisheries in California, ours are motivated primarily from our work with low-head (~3–5 m) dam removals in the Midwest and the proposed removal of dams on the Elwha River in Washington State, USA.

Environmental Decision-Making

Making decisions on environmental issues is often a difficult and contentious process. Fundamental understanding of the physical and biological processes governing environmental systems is inhibited by their complexity, which generally precludes a simple reductionist approach to management (Ludwig and others 1993). When fundamental understanding of environmental systems is lacking, scientific consensus, and thus policy, are often many years or decades away. Even when scientific consensus does exist in environmental matters, policy decisions will not necessarily reflect the views of the overall scientific community, often because industrial or resource use practices were set in place long before their environmental ramifications were understood or documented (Ludwig and others 1993). Lack of agreement between policies and scientific consensus, as well as the adoption of ineffective policies, can also be the result of vague or incomplete overall goals underlying development of the policy (Angermeier and Karr 1994). Two critical facets of environmental policy, then, are (1) scientific understanding and (2) clarity of purpose.

Shannon (1998) summarized these two aspects of environmental decision-making in a four-stage typology of how organizations approach decisions, based on purposes and objectives in combination with available science and its application. In this typology (Table 1), purposes are clear when there is a single overarching objective and when there is a single organization with jurisdiction. Such clarity of purpose does not necessarily lead to environmentally beneficial decisions. For example, the era of large dam construction in the United States (mid-20th century) represents a time when the Bureau of Reclamation had a clear mandate to provide water and hydroelectric energy to developing western cities. Purposes become ambiguous when several objectives must be achieved or when several diverse organizations have potential jurisdiction.

Table 1. Typology of environmental decision-making processes[a]

	Purposes clear	Purposes ambiguous
High scientific certainty	Use computational methods to make decision	Bargain and advocate position using technical competence
Low scientific certainty	Develop experimental program	Build consensus for decisions

[a]Adapted from Shannon (1998).

It is also critical that the science on which managerial decisions are based is accurate, i.e., based on sufficient data and appropriate analysis. "High scientific certainty" implies an understanding of the underlying fundamental physical and/or biological processes, and the development of appropriate management routines for its application. "Low scientific certainty" implies that the underlying processes are poorly understood, the managerial knowledge is undeveloped, or the organizational policies for knowledge-based management are inadequate. For example, removal of the Ft. Edward dam on the Hudson River in 1973 resulted in the blockage of downstream canals with sediment and the transport of previously stored PCB-contaminated sediment to downstream reaches (Shuman 1995). Rulings by the Federal Power Commission in 1977 found that preremoval studies were ambiguous and imprecise in determining whether dam removal should be authorized (Shuman 1995). The Ft. Edward case provides a profound example of a dam removal case where there was little or no science-based consideration of environmental impacts prior to the removal decision and of the potential consequences that can occur in the absence of such consideration.

Agencies faced with scientific uncertainty often adopt an adaptive management strategy, in which policies are changed as the underlying science of the problem becomes more certain. Science can assist in developing effective environmental policy if greater scientific certainty is developed (Table 1). It is important to examine where dam removal stands in terms of both understanding of fundamental physical and biological processes, as well as how available scientific understanding has been applied to dam removal cases.

Science of Dam Removal

While dam removal is becoming more common, particularly for small dams, the science of predicting environmental effects of small or large dam removal remains in its infancy. More than 200 dams have been removed in the United States in the past 30 years, although more than 90% of those removed are less than 15 m tall (American Rivers and others 1999; Doyle and others 2000). Despite this large number of dam removals, fundamental information about environmental impacts associated with dam removal is rarely documented (Shuman 1995, Doyle and others 2000, Bednarek 2001). We briefly examine two specific scientific areas—geomorphology and ecology—and how agencies have proceeded with dam removal decisions in the absence of well-developed science.

Geomorphic Impacts

There is a rich literature documenting the effects of dam presence and operation on river morphology (Ligon and others 1995), but very few studies document or investigate the geomorphic events and changes surrounding dam removal. Almost all studies of dam removal to date provide insufficient description of pre- and postremoval sediment storage and movement (Shuman 1995), although preliminary results of a limited number of new studies on small dam removals are starting to emerge (e.g., Evans and others 2000, Stanley and others 2002, Doyle and others 2002). The relative quantity of sediment transported from reservoirs following dam removal ranges from 10% to 80% of the stored reservoir sediment, and most of this sediment is mobilized during the first year following removal (see review by Doyle and others 2002). The distance this eroded sediment travels before being deposited and the rate at which it is transported downstream are critical issues surrounding dam removal, but the ability to predict these processes is weak (Wohl and Cenderelli 2000, Pizzuto 2002, Doyle and others 2002).

Initial loss of a significant portion of the reservoir sediment should not be taken to mean that overall channel response to dam removal is equally rapid. The limited empirical data of channel morphology following dam removal suggest that channels may take years to develop in former reservoir sites and that the equilibrium channel condition may be substantially different from the conditions present prior to dam construction (Lenhart 2000, Doyle and others 2002). Proposed methods to stabilize reservoir sediment following dam removal are often based on the assumption that the river will adopt its predam configuration or that the configuration of the developing channel soon after dam removal is reflective of equilibrium conditions (Stoker and Harbor 1991, American Society of Civil Engineers 1997). In light of the limited empirical data available, such assumptions need critical evaluation because they are not consistent with the limited empirical data available from recent small dam removals. Because of the discrepancies between assumptions and the limited data, reliable quantitative predictions of channel form following dam removal are currently not possible. Given current knowledge, sediment stabilization strategies for small dam removals will need to rely on geomorphic analogies (e.g., Pizzuto 2002, Doyle and others 2002), whereas sediment stabilization for large dam removals will need to be based on both geomorphic analogies and the scaling-up of observations from small dam removals.

Ecological Impacts

There has been extensive scientific documentation of the profound negative effects of dams on all levels of ecological organization in rivers (e.g., see Baxter 1977). As is the case for the physical environment, however, there is little published quantitative research documenting the ecological effects of dam removal. The existing empirical studies on ecological response to dam removal are limited to a few small dam removal cases, and these suggest that fish and macroinvertebrate communities can recover to predam conditions over the time scale of months to years (Kanehl and others 1997, Stanley and others 2002), while vegetation communities may require decades to centuries (Lenhart 2000).

In addition to variable rates of change over time, different trajectories of postremoval succession may be possible, depending on timing and mode of dam removal or prevailing conditions following removal (Stanley and Doyle 2002). Salmon response to dam removal provides an excellent example of the variable recovery patterns possible in response to dam removal. Simulation studies suggest that the removal of the Elwha Dam in Washington will have "major adverse short-term impacts on salmon attempting to return or spawn in the river" (National Park Service 1996). Suspended sediment loads associated with breaching are expected to reach lethal levels during some phases of the removal. Consequently, the removal schedule would be designed such that sediment releases occur when salmon are not in the river. If scheduling is successful, then it is reasonable to expect populations to recover to preimpoundment densities. Mismatches between expected time of fish runs and the removal schedule, or an unanticipated flood that mobilizes large amounts of sediments could devastate remaining populations. In this case, timing of the dam removal and a certain degree of luck play a critical role in dictating the subsequent recovery pattern of the fish.

Decisions in the Absence of Compelling Science

Decisions about dam removal are being made despite the absence of advanced scientific understanding and extensive empirical data. In most small dam removal cases, scientific understanding plays a minimal role in decision-making because of the lack of funds for preliminary studies, because the environmental impact of removing small structures is expected to be minimal, and because issues other than the environment, such as safety, are the driving reason for the dam being removed (Born and others 1998, Doyle and others 2000).

For the proposed removals of large dams, the most common way in which some scientific understanding is applied to decision making is through the use of simulation models (e.g., Harbor 1993, Wik 1995, Beck 1998). Simulation models draw upon and apply existing scientific knowledge in related areas, and thus provide a practical way to bring science into decision-making. Simulation models are also attractive because they can be used to assess alternative management actions (e.g., repair versus removal), and thus may serve as the basis for decisions on whether or not to remove a dam as well as how to remove the structure (Stoker and Harbor 1991, Wik 1995, American Society of Civil Engineers 1997, Beck 1998, Kareiva and others 2000). Models can also be used to evaluate approaches besides dam removal for alleviating the environmental impacts of dams, which is particularly critical when there are numerous conflicting interests (Smith and others 2000). For example, Kareiva and others (2000) applied a matrix model to long-term salmon population data to explore salmonid mortality associated with dams on the Columbia–Snake River system. They found that river management aimed solely at improving in-river migration survival (i.e., removal of dams) would not necessarily reverse the population decline of chinook salmon in the Snake River, but that survival during both the in-river and estuarine phases needed to be increased to achieve such a management goal. Based on the modeling results, Kareiva and others (2000) suggested that dam removal will not necessarily guarantee restoration of predam populations. Simulation models were also used to predict the transport of sediment following the proposed removal of the Elwha and Glines Canyon dams on the Elwha River, Washington (Harbor 1993). Results revealed the need to increase downstream flood-control levee heights by 0.3–1.5 m following dam removal due to predicted sedimentation in downstream reaches. In addition, the study showed that dam removal would blanket downstream spawning gravels with fine sediment, causing severe negative impacts to downstream biota.

While the results from these studies provide valuable information for decision-making, the appropriateness of the input data used in these models has been questioned (Dambacher and others 2001). In addition, because models applied to dam removal were first developed for other applications and environments, their applicability to the unique circumstances of dam removal needs to be fully assessed (Wohl and Cenderelli 2000). Thus, although models can provide reasonable results (e.g., Williams 1977), this cannot be assumed a priori, and their accuracy for a range of conditions must be evaluated (e.g., Rathburn and Wohl 2001) as part of the processes of developing compelling science to support decision-making. There is the possibility that modeling approaches yield potentially misleading results, which substantially compromises the integrity of policies based on these results (Trimble and Crosson 2000). Despite potential limitations, models do represent a valuable way to bring existing scientific understanding to the development and evaluation management decisions and for identifying critical gaps in data and understanding. As scientific understanding improves, this new knowledge can be integrated into decision-making, in part by refining and updating simulation models.

Purpose of Dam Removal

Clearly defining purposes for dam removal is also critical to decision-making (Table 1). The mission of the agency responsible for the dam removal decision typically controls the purposes that underlie consideration of dam removal, the clarity with which these are defined, and the attitude and approach to the prospect of dam removal. There is often an inherent contradiction between an agency's mission (which is, in part, achieved through dam operation) and dam removal. Therefore it is not surprising that most agencies have dealt with potential removal cases individually and have viewed removal as a costly economic alternative because of the apparent conflict between removal and the agency's mission (e.g., see Jamieson and others 1999). Furthermore, decisions regarding dam removal do not typically proceed via a centralized or consistent process (Bowman 2002). This case-by-case approach is acceptable when the number of dams requiring evaluation is small and few decisions or choices must be made. As dams and reservoirs age, there will be a steady increase in the population of dams in need of maintenance, repair, or removal (Pyle 1995). As these numbers increase, a clearer definition of how decisions are made will be needed. Given the finite resources of agencies and a potentially enormous number of dams that will need to be evaluated, many agencies will quickly reach the point where they must decide not only whether or not to remove specific dams, but how to prioritize dam removals.

The purpose of a removal also has a direct impact on how a dam gets removed and, thus, project cost. For many small dam removals, removing a safety liability is the primary concern and the reason why dam removal is being considered. In these cases, dams should be removed as quickly and inexpensively as possible. If environmental restoration is the chief motive for removal, then gradual reservoir draining, or staged removal may be used to decrease downstream sedimentation, nutrient loading, and other possible environmental impacts (e.g., Harbor 1993). Staged removal, however, exposes saturated and potentially unstable reservoir sediments for long periods and requires expensive repeated mobilization of construction crews, increasing the liability and costs of a removal project. Such additional costs may be insignificant for large dam removals, but can represent a significant economic consideration for small dam removal cases. The overriding purpose for removing a dam, then, can have profound influences on the methods and costs of removal, so purpose must be clearly defined in addressing dam removal.

Suggested Policies and Strategies

Thus far we have shown that the science behind dam removal is uncertain and the purpose is often ambiguous, and these have implications for how decisions should be made (Table 1). Specifically, dam removal is at the stage of "organizational learning" wherein agencies are in an adaptive position relative to problems and solutions and should act less as an advocate for their favored solutions and more as a participant in deliberating problems and negotiating potential solutions (Shannon 1998, Smith and others 2000).

Once agencies arrive at a clear purpose for dam removal, the task of establishing the underlying science of dam removal should be undertaken via experimentation and adaptive management. In this context, agencies would treat initial dam removals as experiments wherein environmental impacts of the removal, various removal methods, and even nonremoval options are studied through pre- and postremoval modeling and monitoring. Subsequent decisions and analyses surrounding dam removal would then incorporate these findings. This type of decision process requires technical expertise, but it acknowledges that decisions must initially be negotiated based on insufficient information.

To move from the current state of dam removal towards more clearly defined purposes and better scientific understanding, agencies would benefit by implementing two specific policies: (1) adoption of prioritization schemes for dams to be removed, and (2) establishing a minimum level of analysis for the decision of whether to remove a dam and/or how to remove a dam.

Prioritization

Given the finite resources of the agencies and organizations that are responsible for dam management, there is an obvious need for decision-makers at various levels of government to prioritize potential dam removal sites (e.g., see Figure 1). Establishing a prioritization scheme for dam removal requires addressing two questions. First, what is the purpose for maintaining or removing dams within the agency? Second, what characterizes important (as defined or perceived by the managing agency) dams or dam removal sites? Large-scale planning and clarification of purpose is needed prior to removing numerous dams and also helps develop a selection process for projects to optimize use of limited funds. Such basin-level planning and analysis was conducted by the state of Maine prior to, and as an integral part of, the recommendation for the removal of the Edwards Dam on the Kennebec River.

There are numerous potential criteria that can be adopted for prioritizing dam removals (e.g., Pejchar and Warner 2001). We have suggested some specific criteria below, although others not included are expected to be relevant, depending on the types and sizes of dams for which an agency is responsible: (1) reducing greatest safety risks, (2) economics, (3) establishing complete free-flowing river corridors, (4) improving survivability of target/sensitive species, and (5) enhancing ongoing or proposed river restoration projects. Our suggestions and those of Pejchar and Warner (2001) may be valid for specific types of agencies and dams within those agencies, but alternative criteria will need to be developed for other agencies. An example of how this variance affects dam removal decisions is also described below.

Greatest safety hazards. Safety and liability issues surrounding aging dams are often the driving factors in

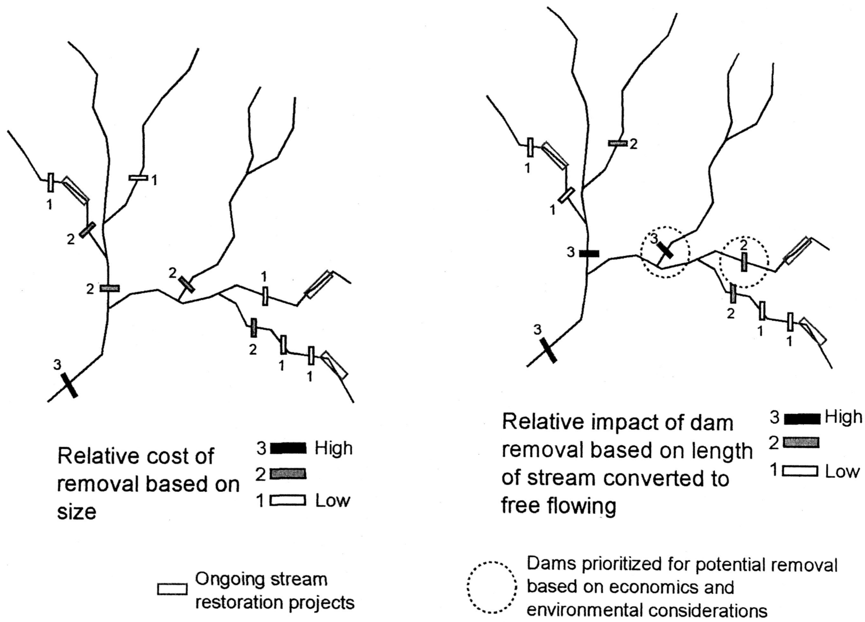

Figure 1. Conceptual example of prioritizing dam removals based on economics and environmental factors. Removal of circled dams would create the greatest free-flowing stretch of river at the lowest cost and also allow connection of the main river with an ongoing stream restoration project.

the emergence of a potential removal, particularly for small dams. For example, in 13 of 14 dam removal cases in Wisconsin examined by Born and others (1998), a safety inspection, dam failure, or a perceived safety risk was the instigating event in the removal process. The managerial routines for assessing the structural integrity of agency dams and risk assessment are already in place and active (e.g., Achterberg 1999, Bryant 1999, Pearre 1999, Wagner 1999) and could be extended or modified for the application of dam removal as an alternative.

Economics. Closely associated with safety hazards and liability issues, economic considerations are often the deciding factor for choosing removal over repair, and there are several reasons why economics should continue to be a priority for dam removal policies and decision-making. Many state and federal agencies are required to apply cost–benefit analysis in planning for water resources projects (Huppert and Kantor 1998), and while this practice has been criticized (NRC 1992), it has also received support (Arrow and others 1996). This type of analysis has commonly led to small dam removal, because removal is often less expensive than repair (Born and others 1998). Further, the use of economics to decide which dams to remove optimizes the application of limited financial resources.

While economics as a criterion could potentially maximize the number of dams that ultimately get removed, it may not provide the greatest ecological benefit. For instance, a single mainstem dam blocks fish passage to the entire upstream channel network and its removal might yield the greatest benefit to the fishery. However, its removal would be disproportionately more expensive and time consuming than an ecologically less beneficial option of removing several headwater dams (cf. Stanley and others 2002, Stoker and Harbor 1991, Wik 1995).

Cost–benefit analysis is a numerical approach that applies economics to environmental decision-making (e.g., Hyman and Leibowitz 2000). We have suggested that such approaches are appropriate only when science is fairly well known and when purposes are clear (Table 1). As shown earlier, the science related to dam removal is not well known nor are the overall purposes driving dam removal. Further, growing evidence suggests that economics of dam removal decisions are not straightforward (Loomis 1996, Whitelaw and MacMullan 2002) nor are choices to remove dams economically expedient (Grant 2001). It is thus premature to use a highly automated process of computational cost–benefit analysis as the basis for decisions relating to dam removal, although this may be a valid component of a prioritization method in the future.

Establish an entire free-flowing riverine system. Uninterrupted aquatic and riparian corridors provide critical habitat and migratory pathways for bird and fish species. Therefore, dam removals that open up long river reaches may become priority sites for fish and wildlife-related management agencies. In most cases, reestablishment of an entire free-flowing river from headwaters to the ocean is unrealistic because there will likely be little political or financial support for the removal of one or more large structures on a downstream river.

Even in the presence of immovable mainstem structures, uninterrupted flow of large sections of a drainage basin can be reestablished by the removal of a few small dams. Uninterrupted flow throughout a headwater (first to fourth order) watershed may be achieved by removing one or a few dams on the mainstem channel. As a case in point, the removal of four remaining dams over the past six years from the mainstem of the Baraboo River, Wisconsin created 185 km of free flowing river channel. This length of uninterrupted channel stands in stark contrast to the statewide average of one dam every 14.5 km of river (Gebken and others 1995). Interestingly, the Prairie du Sac Dam, approximately 3 km downstream of the confluence of the Baraboo and Wisconsin rivers, represents the sole migratory barrier between the headwaters of the Baraboo River and the Gulf of Mexico.

Target species. Dams have profound effects on anadromous fish species through blockage of migration corridors. While Pacific salmon have been the hallmark group for dam removal (e.g., Pejchar and Warner 2001), other species are also vulnerable to dams. Movement of several salmonid and nonsalmonid taxa are constrained by the presence of dams, and restriction of fish movements by dams also contributes to declines of the most threatened and endangered group of organisms in US waters—the unionid mussels (Watters 1995, Vaughn and Taylor 1999). Anadromous fishes may return quickly following dam removal; runs of striped bass, Atlantic salmon, and American shad returned to previously inaccessible sections of the Kennebec River, Maine, only one year after the removal of the Edwards Dam (McGillvray 2001).

The advantage of using recovery of target species to prioritize dams for removal is that it appears relatively straightforward in that key migration barriers assume highest removal priority. There are several disadvantages, however. First, it is often the large, mainstem dams that have the greatest impact on fish migration, limiting access to the upstream main channel and tributaries. These dams are often the least likely to be removed due to costs involved (Wik 1995) and their high power production in comparison to their smaller, headwater counterparts. Second, barriers created by dams may serve a desirable management purpose. For example, removal of the Marmot Dam in Oregon has been opposed in part because the dam currently separates hatchery salmon stocks from wild stocks, some of which are listed by the National Marine Fisheries Service as threatened (ODFW 1999). Similarly, low-head weirs have been constructed in many tributary streams of the Great Lakes to prevent spawning runs of parasitic sea lampreys (McLaughlin and others 2001). Further, removal of a low-head dam in Wisconsin resulted in almost 100% mortality of unionid mussels within the former impoundment due to exposure, and additional downstream mortality due to burial (Stanley and Doyle, personal observations), exemplifying the potential adverse impacts of dam removal on local biota. The seemingly straightforward goal of enhancing habitat or migration for target species through selective dam removal may be complicated by costs to other taxa. These sorts of trade-offs of single-taxon management strategies are generally well known in resource management, and have, in part, resulted in the recent shift toward whole-ecosystem management (e.g., Haeuber and Franklin 1996).

Enhance ongoing or proposed river restoration projects. More often than not, river restoration projects are small-scale (10^2–10^3 m) projects consisting of the manipulation of hydrology, geomorphology, or local vegetation to ameliorate previous environmental damage. There is growing emphasis on incorporating common river restoration projects into overall watershed restoration plans (Shields and others 1999), although the novelty of dam removal has precluded its consideration in most restoration efforts to date (Federal Interagency Stream Restoration Working Group 1998).

Dam removal, coupled with traditional restoration, can be used to greatly enhance the environmental quality and recreational use of a river, as well as the environmental benefits of dam removal (e.g., Kanehl and others 1997). Much of the work needed to design and construct a river restoration project (e.g., data, analysis, heavy equipment) is similar, if not identical to the work needed to remove a dam (cf. Federal Interagency Stream Restoration Working Group 1998, American Society of Civil Engineers 1997), so coupling river restoration efforts with dam removal can potentially reduce the duration and costs of both projects. The location and timing of ongoing or proposed river restoration efforts can then be used as a prioritization factor for decisions surrounding potential removal of dams.

Examples from the Edwards Dam and Woolen Mills Dam. Two cases of dam removal provide examples of how the decision to remove dams can be heavily influenced by an individual agency's responsibility and, thus, on how priorities can vary between agencies. While many agencies do not have dam removal policies in place, the Federal Energy Regulatory Commission (FERC) is a notable exception. FERC issued its policy statement on dam removal in December 1994 and first implemented this policy in 1997 in its refusal to relicense the Edwards

Dam on the Kennebec River, Maine (Bryant 1999). Another exception is the Wisconsin Department of Natural Resources, which, due to its proactive state dam safety program, has removed more dams than any other state (American Rivers and others 1999, Born and others 1998), including the Woolen Mills Dam in 1988.

The Edwards Dam Project (see review by Bryant 1999) filed for relicensing with FERC in 1991 and proposed to expand electricity generation and to mitigate environmental damages by providing limited fish passage and recreational facilities. However, the environmental impact statement evaluating both the watershed environmental condition and the relicensing decision concluded that the best available fish passage facilities would fail to restore the entire fishery and that only dam removal would restore the unique river environment upstream of the dam. The Edwards Dam was an active hydroelectric dam, although it provided only 0.1% of Maine's total electricity supply, and its electricity was being purchased for a price five times above the market rate by contract with Central Maine Power. An economic analysis showed that dam removal would cost $2.7 million compared to $10 million for dam modifications. Dam modifications would only partially mitigate environmental damages, while rendering the dam uneconomic. Based on this analysis, FERC denied the license and ordered decommissioning and removal, which occurred in 1999.

In contrast to the Edwards Dam, the Woolen Mills Dam ceased power production in 1959 and was abandoned by its owners. In 1980, the dam was declared a public safety hazard by the state due to structural flaws, and the town, to which ownership had been transferred, was held responsible by the state for removing or repairing the dam. Repair costs were estimated at $3.3 million, compared to the $80,000 cost of removal. The dam was removed in 1988. While not explicitly considered during the removal decision, the Woolen Mills Dam removal has become a part of a larger comprehensive effort to restore water quality and habitat throughout the Milwaukee River basin, i.e., dam removal has been coupled with other river restoration efforts.

These two cases illustrate how different agencies are faced with different types of dams, which affect the relevant considerations in dam removal. While fish passage and environmental concerns were the motivating reason for the Edwards Dam not being relicensed, safety concerns drove the Woolen Mills case, as well as most small dams already removed in Wisconsin (Born and others 1998). In both cases, the dominant reason for removal could have been overcome, at least partially, given sufficient money for repair and modifications. Repair costs far exceeded removal costs, however, and the economic return for repair was negligible, so removal was the preferred alternative economically. In both cases, economics was a secondary, although very significant factor in the decision process.

Minimum Level of Analysis

Policies regarding dam removal should account for the current lack of scientific knowledge and should foster increased scientific development. Establishing a minimum level of analysis as a basis for deciding whether or not to remove a dam and/or how to remove a dam will force appropriate preremoval data collection, which will increase understanding of environmental impacts of dam removal. A standard minimum level of analysis will not be applicable in all regions of the country or for all types of dams. Such standards will need to be developed specifically within individual agencies based on the types (e.g., size and function) of dams with which they work and will need to be adaptively modified as lessons are learned from dam removals.

There are several specific issues that should be considered during the decision-making process for most, if not all dam removal projects. First, the potential impact of a dam removal on endangered species. Some endangered species will benefit from a dam removal (e.g., anadromous fish), although others could suffer large losses (e.g., unionid mussel communities in Midwestern streams). Second, the chemical quality of the impounded sediment is a critical concern. Contaminated sediment stored in a reservoir is easier to remove than the same sediment transported and deposited over several hundred meters to kilometers downstream [e.g., the Fort Edward dam removal on the Hudson River (American Rivers and others 1999)]. Finally, how dam removal will impact the stability or functionality of engineered structures must be addressed. Removal of a flood control dam, or downstream sedimentation because of dam removal, may necessitate increasing heights of downstream levees or modifying bridge abutment structures because of potentially increased peak flows.

These considerations are only broad suggestions, and addressing them will necessitate data collection and simulation modeling. Data collection and subsequent analysis should serve as the foundation for an evaluation of whether or not, or how to remove a dam. A comprehensive review of data relevant to dam removal studies is given by the American Society of Civil Engineers (1997). Not all of the types of data listed will be necessary for every project, because different types of dams, and different physiographic settings require different kinds of information to assess removal or repair potential. The list would need to be reviewed and modified to reflect the actual needs of the types of dams overseen by a given agency, and then that subset of data requirements may be made even more specific for a particular project. However, we suggest that agencies faced with dam removal develop a standard for the minimum data to be collected at a given site and a minimum level of analysis in order to reduce the chances for scenarios like the Fort Edward dam case.

Collection of preremoval data from numerous sites as a prerequisite for removal of any dam is also critical to monitor the successes and failures of dam removal projects of various scales. Preliminary data should consist of both physical and ecological characteristics (American Society of Civil Engineers 1997) to fully document the changes caused by the removal of a dam. Further, post removal monitoring programs should be established for several years following dam removal, as well as long-term monitoring programs at selected sites to document the short- and long-term physical and ecological changes induced by dam removal (see also Bednarek 2001). Postremoval monitoring should be completed (or administered) by the agency responsible for the removal because current science does not fully support removal as a viable means of reversing environmental degradation (cf. Kanehl and others 1997, Kareiva and others 2000), leaving the responsibility of proof of its efficacy on the agency in charge of removal. Unfortunately, given the budgetary constraints under which most agencies operate, postremoval monitoring is often sacrificed.

Previous studies have used monitoring programs to document the impact of dam removal on fish (Kanehl and others 1997), macroinvertebrates, (Stanley and others 2002), and geomorphology (Williams 1977, Wohl and Cenderelli 2000). Monitoring programs following environmental river restoration projects (Kondolf and Micheli 1995) could also be used as a template for monitoring dam removal projects. Additionally, dam removal is a unique opportunity to obtain valuable information about physical and biological response and recovery to a disturbance (Stanley and Doyle 2002), and monitoring programs should also be designed to ask specific questions related to these issues. Example questions that could be addressed by monitoring programs during early dam removal studies are: (1) Is ecological recovery of predam conditions possible and over what timescales does it occur? (2) What quantity of sediment is eroded from the reservoir, how quickly is it eroded, and how far downstream is it transported? (3) What effects do the size of dam removed or various removal strategies have on the severity of physical and ecological disturbance?

The adoption of preremoval data collection and postremoval monitoring will move agencies into the "experimental" stage of the decision-making process wherein lessons from previous projects are quantitatively documented (Table 1), and thus can be applied to future projects and used to adapt policies. In particular, the accuracy of simulation of models, which lies at the core of large dam removal proposals, can be assessed for small dam removals where failure of a project may not be as severe. If adequate postremoval monitoring is not conducted, then the success and failure of various projects and/or removal methods will not be known at a level that is needed to support changes in dam removal policy and approaches.

The advantages of establishing some minimum level of analysis are quite clear, but so are the disadvantages. Preliminary data collection and analysis will increase the cost and time associated with removing a dam, particularly small dam removal projects. It is expected that implementation of minimum level of analysis standards will reduce the overall number of dams that an agency can remove. This is particularly true because financial resources that could otherwise be used for removal of dams will be used for conducting studies. The insight gained from preliminary data collection and postremoval monitoring, however, is critical for planning future dam removals with the greatest chance of success. Indeed, in their examination of the effects of dams and dam removal on salmonids in the Columbia River system, Kareiva and others (2000) concluded that, "Given the current uncertainty, policy-makers may have to view the decisions they make as large experiments, the outcomes of which cannot be predicted but from which we can learn a great deal pertaining to endangered salmonids worldwide." In the long term, investing in pre- and postdam removal analysis will pay off in terms of increasing the effectiveness of removal prioritization and the success of dam removal projects in achieving the goals of agencies.

Conclusions

Within a relatively short time frame, dam removal arrived on the national stage as a hotly debated political and scientific issue (Grant 2001), and while the vagaries of current events mean that discussion of dam removal may fade out of view with equal rapidity, dam management will become an increasingly pressing issue for environmental management agencies as dams get older and more costly to maintain. Unfortunately, there is a lack of both fundamental science and basic policy frameworks in which to base decisions regarding dam management and removal in the United States. To remedy this situation, agencies must become introspective and consider long-term priorities and realities for the management of an aging infrastructure. Further, agency–research partnerships should become involved in an experimental phase of dam removal wherein the number of dams removed is initially kept small so that we can develop our fundamental understanding from these case studies to support effective decision-making in the future. This approach will temporarily redirect some funds from removing dams to dam removal monitoring and research, but the additional information and understanding gained will be critical to increasing the effectiveness of future decisions.

While the discussion of dam removal may or may not fade from the political stage in the next five years, it is sure to return in years to come because of the inevitable aging of dams (cf., Miles 1978, Grant 2001). The time to establish sound science and policy to cope with the inevitable management need is before that time when extreme economic or safety concerns caused by declining or failing dam operation necessitate hasty and poorly formulated management actions.

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